UNCLASSIFIED

AD NUMBER
ADB008179
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; OCT 1975. Other requests shall be referred to Air Force Flight Dynamics Laboratory, Attn: FEE, Wright Patterson AFB, OH 45433.**
AUTHORITY
AFFDL ltr, 27 Dec 1977

THIS PAGE IS UNCLASSIFIED

THIS REPORT HAS BEEN DELIMITED AND CLEARED FOR PUBLIC RELEASE UNDER DOD DIRECTIVE 5200.20 AND NO RESTRICTIONS ARE IMPOSED UPON ITS USE AND DISCLOSURE.

DISTRIBUTION STATEMENT A

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFFDL-TR-75-104

DESIGN, ASSEMBLY AND INSTALLATION OF ELECTRONIC CONTROL CIRCUITS FOR VM COOLER DRIVE MOTORS

PHILIPS LABORATORIES
A DIVISION OF NORTH AMERICAN PHILIPS CORPORATION
BRIARCLIFF MANOR, NEW YORK 10510

OCTOBER 1975

TECHNICAL REPORT AFFDL-TR-75-104
FINAL REPORT FOR PERIOD 3 JUNE 1974 – 6 JUNE 1975

Distribution limited to U.S. Government agencies only; test and evaluation; statement applied October 1975. Other requests for this document must be referred to AF Flight Dynamics Laboratory, (FEE), Wright-Patterson AFB, Ohio 45433

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

This technical report has been reviewed and is approved for publication.

William L. Haskin
WILLIAM L. HASKIN
Project Engineer

FOR THE COMMANDER

WILLIAM C. SAVAGE
Chief, Environmental Control Branch
Vehicle Equipment Division
Air Force Flight Dynamics Laboratory

AIR FORCE - 17-11-75 - 100

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
AFFDL-TR-75-104

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
DESIGN, ASSEMBLY AND INSTALLATION OF ELECTRONIC CONTROL CIRCUITS FOR VM COOLER DRIVE MOTORS

5. TYPE OF REPORT & PERIOD COVERED
Final Report.
3 Jun[redacted] [redacted]974-6 Jun[redacted] [redacted]75

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Richard Geyer

8. CONTRACT OR GRANT NUMBER(s)
F33615-74-C-3081

9. PERFORMING ORGANIZATION NAME AND ADDRESS
PHILIPS LABORATORIES
A Division of North American Philips Corp.
Briarcliff Manor, New York 10510

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
AF
~~Project No.~~ 2126
~~Task No.~~ 212603

11. CONTROLLING OFFICE NAME AND ADDRESS
AIR FORCE FLIGHT DYNAMICS LABORATORY
Wright-Patterson Air Force Base, Ohio 45433

12. REPORT DATE
Oct[redacted]75

13. NUMBER OF PAGES
30 p

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U. S. Government agencies only; test and evaluation; statement applied October, 1975. Other requests for this document must be referred to AF Flight Dynamics Laboratory, (FEE), Wright-Patterson AFB, Ohio 45433

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Vuilleumier Cycle Cryogenic Refrigerator
Drive Motors
Electronic Control Circuits
Motor Control Circuits

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program involved the design, assembly, and installation of new electronic control circuits for the drive motors of the Vuilleumier (VM) cycle cryogenic refrigerator that has been developed under Contract No. F33615-71-C-1024. The original design and test results were examined. One of the objectives of the redesign was to have a 95% probability of operating 5,000 hours without failure. The reliability analysis indicates that this has been achieved.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

387334

1B

PREFACE

This final report was submitted by Philips Laboratories, a Division of North American Philips Corporation, Briarcliff Manor, New York under Contract F33615-75-C-3081. The work at Philips Laboratories was under the direction of Mr. Richard Geyer who wrote this report. The contract start date was 3 June 1974, and work at Philips Laboratories was completed on 6 June 1975. The author submitted this report on 29 July 1975.

TABLE OF CONTENTS

Section		Page
	PREFACE	iii
	LIST OF ILLUSTRATIONS	vi
1.	INTRODUCTION	1
2.	REVIEW OF ORIGINAL DESIGN	3
3.	DESCRIPTION OF FINAL MOTOR CONTROL CIRCUIT	4
	3.1 Design Philosophy and General Description	4
	3.2 Position Sensor, Signal Processor, and Commutation Decoder	7
	3.3 Speed Control	9
	3.4 Switching Regulator	12
4.	PROBLEMS ENCOUNTERED	14
	4.1 Circuit Redundancy	14
	4.2 Position-Sensor Signal Processor	15
	4.3 Current Overload	15
	4.4 Starting Circuit	16
5.	RELIABILITY ANALYSIS	17
6.	TEST RESULTS	21

LIST OF ILLUSTRATIONS

		Page
Figure 1:	Drive Motors..............................	2
Figure 2:	Refrigerator Controller......................	2
Figure 3:	Block Diagram of Motor Controller............	6
Figure 4:	Schematic of Position Sensors and Signal Processors............................	8
Figure 5:	Commutation Decoder.........................	8
Figure 6:	Pulse Width Modulator.......................	10
Figure 7:	Schematic of Speed Control Circuit...........	11
Figure 8:	Schematic of Switching Regulator While Coil #1 Is Being Commutated.................	12
Figure 9:	Drive Motor Efficiency vs. Torque...........	22
Figure 10:	Pump Motor Efficiency vs. Torque............	23

1. INTRODUCTION

Philips Laboratories subcontracted the design, development and fabrication of brushless dc motors and associated electronic control circuits for use in the Vuilleumier (VM) cycle, cryogenic refrigerator developed under Contract No. F33615-71-C-1024. The motors represented a significant advance in the state-of-the art, but the delivered systems proved deficient in several ways.

- Efficiency requirements were not met.
- Speed regulation was not met.
- Electronic components failed under test.
- Portions of the circuitry did not function properly.

The purpose of this contract was to examine the design of the motor controller circuits and to redesign them where necessary. Special attention was given to eliminating the causes of component failure, and to the creation of a design which by a simplified reliability analysis would have a 95% probability of operating 5,000 hours without a failure.

The refrigerator uses three brushless dc motors. Two drive the refrigerator and are referred to as the drive motors; the third drives an oil pump and is called the pump motor. The two drive motors (see Fig. 1) are identical and are operated in parallel with their outputs geared together. The combined rated torque is 38 in.lb. at 420 rpm (188 W); the motors are capable of continuous operation at twice rated torque. The pump motor is rated at 1.1 in.lb. at 1750 rpm (23 W) and can operate indefinitely at 150% overload. All three motors have slotted stators with windings inserted in the slots. The rotors are multiple-pole magnets. The drive motor has 32 poles; the pump motor has 12 poles. The electronic control circuitry for the motors is housed in the refrigerator controller (see Fig. 2). The VM refrigerator is described in Technical Report AFFDL-TR-75-114 which is the final report for the spacecraft VM cryogenic refrigerator development.

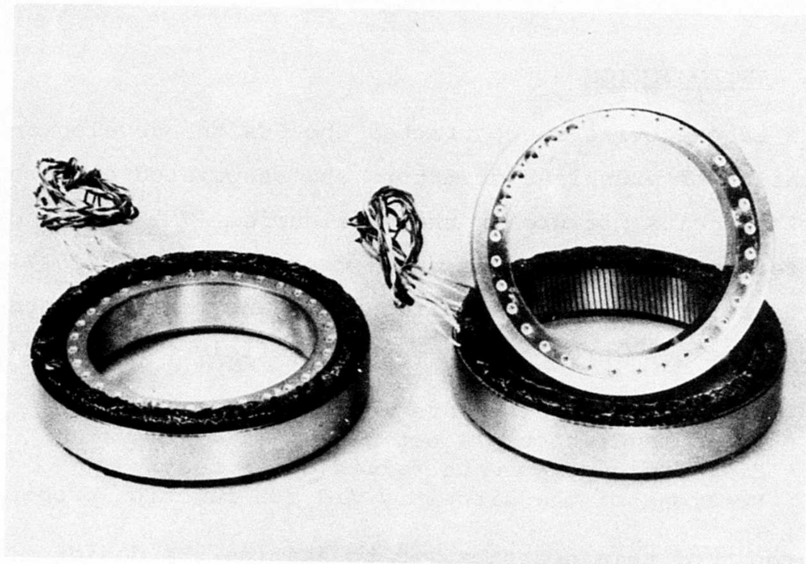

Figure 1: Drive Motors

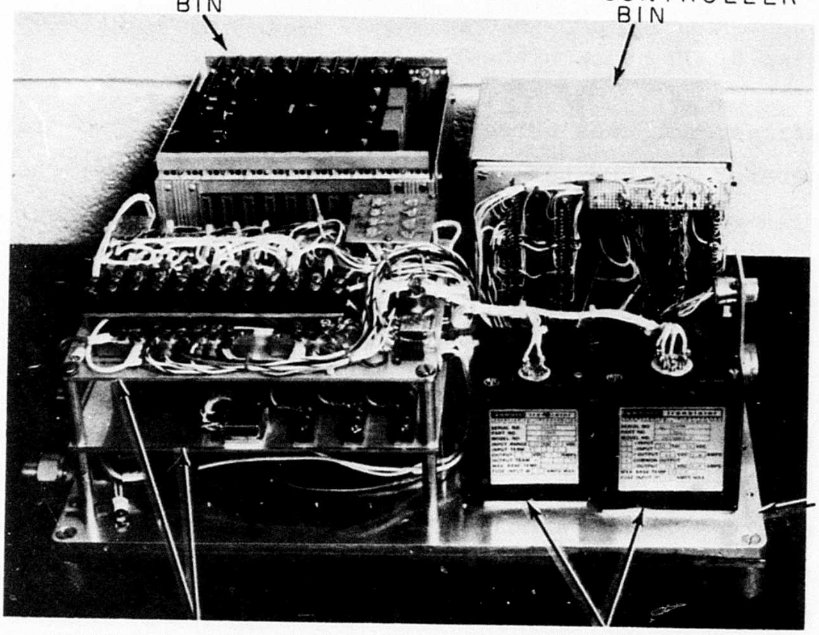

Figure 2: Refrigerator Controller

2. REVIEW OF ORIGINAL DESIGN

A study was made of the original design and test results, and the following conclusions were made:

- The high failure rate of switching transistors was caused by misfirings of the associated coil-dampening SCR's (silicon controlled rectifiers), resulting in current pulses through the transistors in excess of their ratings.
- The SCR's were unduly susceptible to misfirings from noise on the 100 V line. Either the SCR's triggering circuits should be redesigned or a different approach should be taken for coil-dampening.
- The speed control was inadequate and should be completely redesigned.
- The speed and position sensors could saturate at the elevated temperatures they would encounter in the crankcase of the cooler, and, therefore, a different design approach should be used.

3. DESCRIPTION OF FINAL MOTOR CONTROL CIRCUIT

3.1 Design Philosophy and General Circuit Description

One of the major aims of the redesign was to have a 95% probability of operating 5,000 hours without a failure. This represents a mean time between failures of about 100,000 hours, which was nearly five times greater than calculated for the old circuit. This increase in reliability dictated that the number of components be reduced to the bare minimum which would give satisfactory operation. As a result, the following design decisions were made:

- The SCR coil-dampening circuit was abandoned and replaced with a diode scheme in which a single diode across the switching transistor replaced the SCR and the SCR triggering and timing circuits. The penalty paid was possibly a small reduction in the efficiency of the switching regulator.
- The old circuit concept of using the same switching transistors for regulation and commutation was retained. The disadvantage of this over a system where the two functions would be performed separately was a probable increase in switching noise.

An exception to the least-number-of-components philosophy was the position sensor and single processing circuits. The old design used high-gain dc amplifiers which amplified not only the signal but also the dc leakage current from the phototransistors. These were replaced with a more complicated system in which ac-coupled amplifiers were used which amplified the signal but blocked the leakage current.

Another design constraint was physical. The new system had to be installed in the existing VM cooler controller. Since there was no extra space in the controller, the new electronics had to have the same overall dimensions as the old system. It

seemed logical to have the physical layout of the new system duplicate the old system wherever possible to minimize installation problems. In view of the expected decrease in circuit complexity, this seemed feasible.

A block diagram of the motor controller is shown in Figure 3. This diagram is applicable to both the drive-motor and pump-motor controllers, the only difference being that the pump motor does not have a high and low speed select.

The commutation of the motor is achieved with four switching transistors which connect, in sequence, each of the four armature windings to the 100 Vdc supply. The switching order is controlled by the commutator decoder which in turn is controlled by the shaft position sensors.

The position sensor is made of two LED's (light emitting diodes), a commutator disc which is mounted on the motor shaft, and two phototransistors. The position of the shaft is detected by the transmission or obstruction of light passing through the coded commutation disc from the LED's to the phototransistors. The information is decoded and used to drive, in the correct sequence, the armature coils via the switching transistor. A dc voltage proportional to the speed of the motor is derived from the commutation signal.

The speed of the motor is controlled by comparing this voltage with a speed reference voltage, the difference being used to control the width of the 10 kHz pulses which drive the motor.

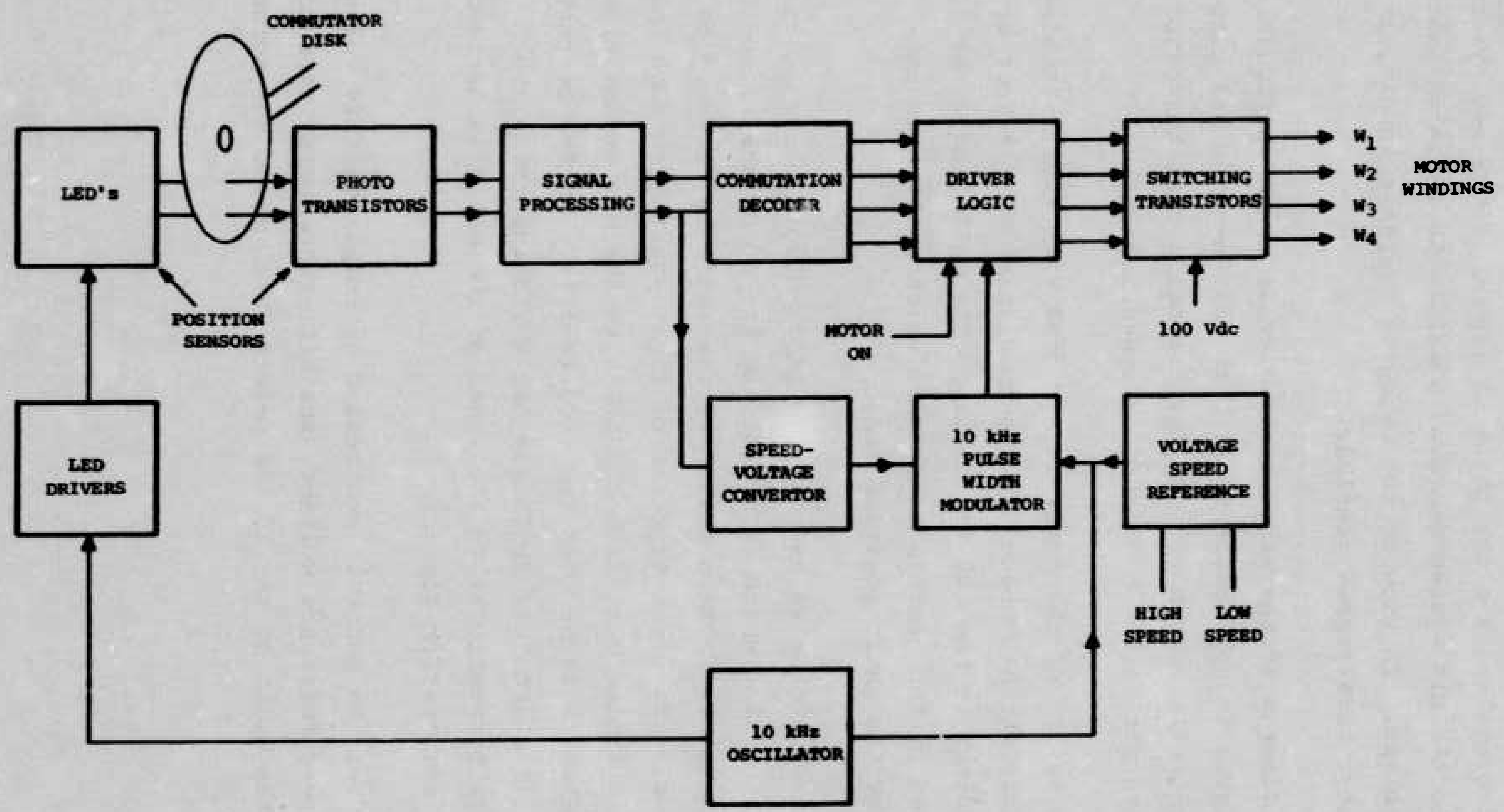

Figure 3: Block Diagram of Motor Controller

3.2 Position Sensor, Signal Processor, and Commutator Decoder

The position sensors operate in a pulse mode. The LED's are pulsed at a 10 kHz rate, and the series of 10 kHz pulses picked up by the two phototransistors are amplified by ac-coupled amplifiers. The amplified series of pulses are then converted to a logical "zero" or "one" commutation signal by two resetable monostable multivibrators (one-shots). Referring to Figure 4, the 10 kHz oscillator made up of U2a and Q5 drives the 20 μs pulse generator U1. The 20 μs pulses energize LED 1 and 2 through Q6 and Q7. The signals from phototransistors D1 and D2 are each amplified by two stages of an ac-coupled amplifier (U12a, U12b, U13a, U13b) and then passed to resetable one-shots (U9a and U9b). The period of these one shots is 120 μs, a bit longer than the period between 10 kHz pulses. As long as the one-shots receive 10 kHz pulses, they remain triggered and their outputs are logical "one". At 120 μs after they have received the last pulse of a series of 10 kHz pulses, they will return to the nontriggered state, a logical "zero". As the rotor turns, the output of the one-shots are square waves 90° apart, the output from channel 1 lagging the output from channel 2. One period of these square waves corresponds to 360 electrical degrees of shaft rotation. The decoder section (Fig. 5) made up of gates U8a, U8b, U7a, U7b, U7c and U7d converts these two channels of square waves into four channels of sequential pulse which go to the coil drivers.

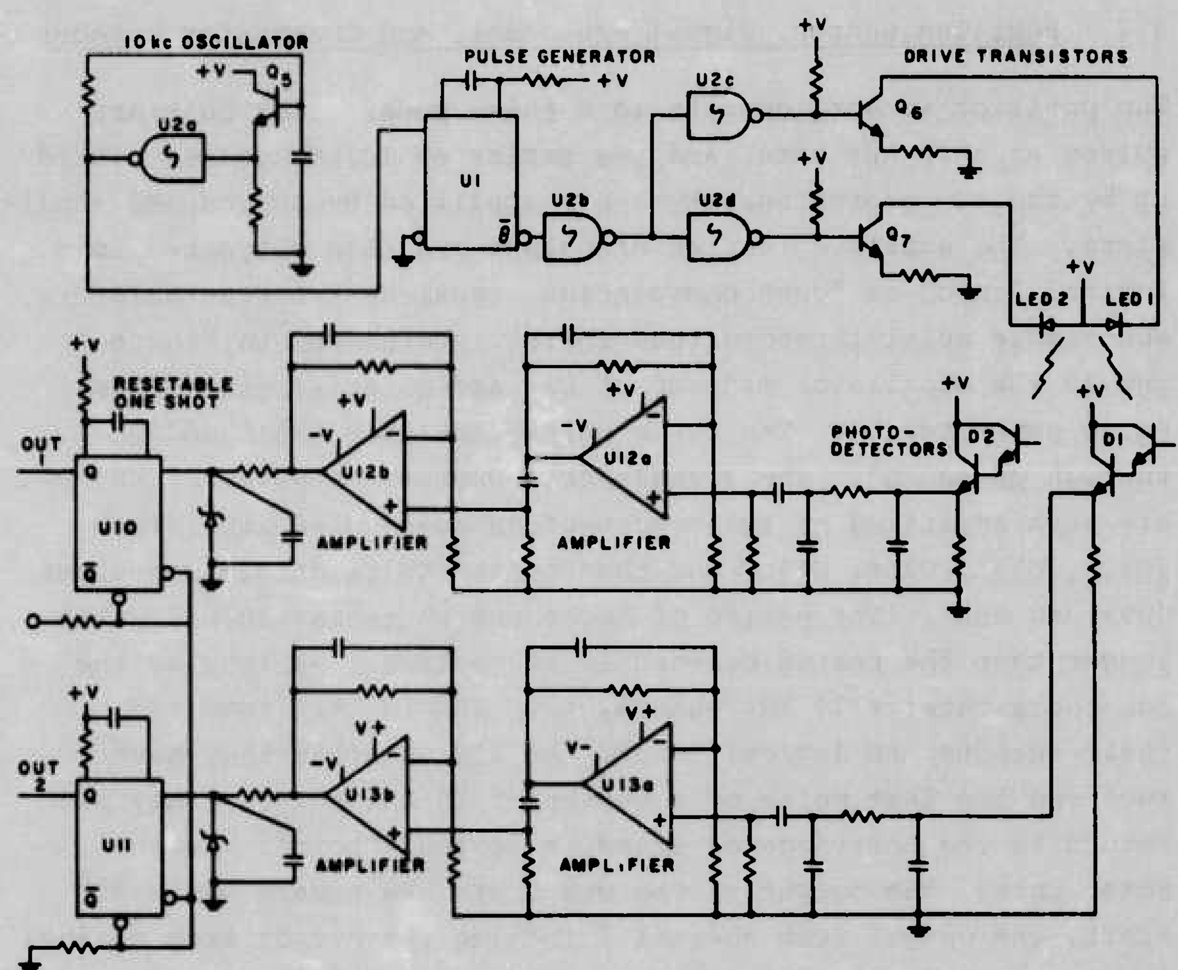

Figure 4: Schematic of Position Sensors and Signal Processors

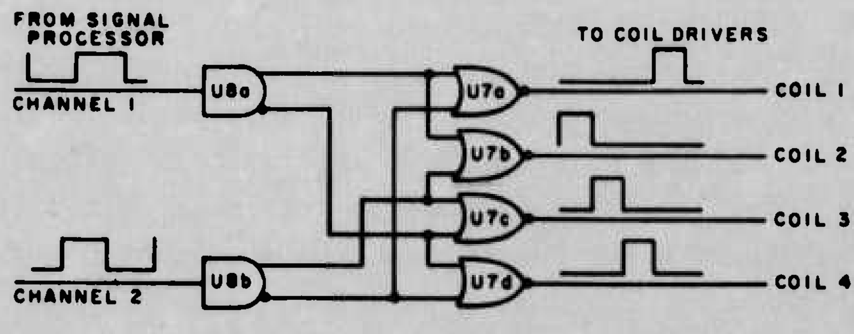

Figure 5: Commutation Decoder

3.3 Speed Control

The pulse width modulator, heart of the motor speed control, translates errors in motor speed into a proportional pulse-width-modulated pulse train. The pulse width modulator is a voltage comparator. The positive input is a dc voltage speed reference on which is superimposed a 10 kHz triangular waveform. The negative input is a voltage which is proportional to the speed of the motor. Figure 6 shows the output of the voltage comparator as the speed of the motor goes from below to above the reference level. When the speed voltage is below the reference, the output is high. As the speed voltage increases, negative 10 kHz pulses are formed whose duration increase until the output is continuously low when the speed voltage is above the reference voltage.

Referring to Figure 7, the commutation signal from U9A is used to trigger the fixed pulse width generator U10. These pulses are averaged to a dc level in integrator U15A. The greater the speed of the motor, the greater the number of pulses per second and the greater the dc voltage produced. U15B inverts the signal from a negative voltage to a positive voltage which is applied to the negative input of voltage comparator U17. The positive dc voltage from U15B also goes through the buffer amplifier U16 where it is available as the speed monitor. The speed reference voltage is developed at the collector of Q4 for normal speed, and at the collector of Q3 for low speed. A triangular wave is generated at the base of Q5 and is added to the reference voltage through the 0.02 μF capacitor. The combined voltage is applied to the positive input of voltage comparator U17. The output of U17 is the pulse-width-modulated pulse train. The pulse width modulation is then gated into each of the four coil drive channels, thereby controlling the amount of power supplied to the motor.

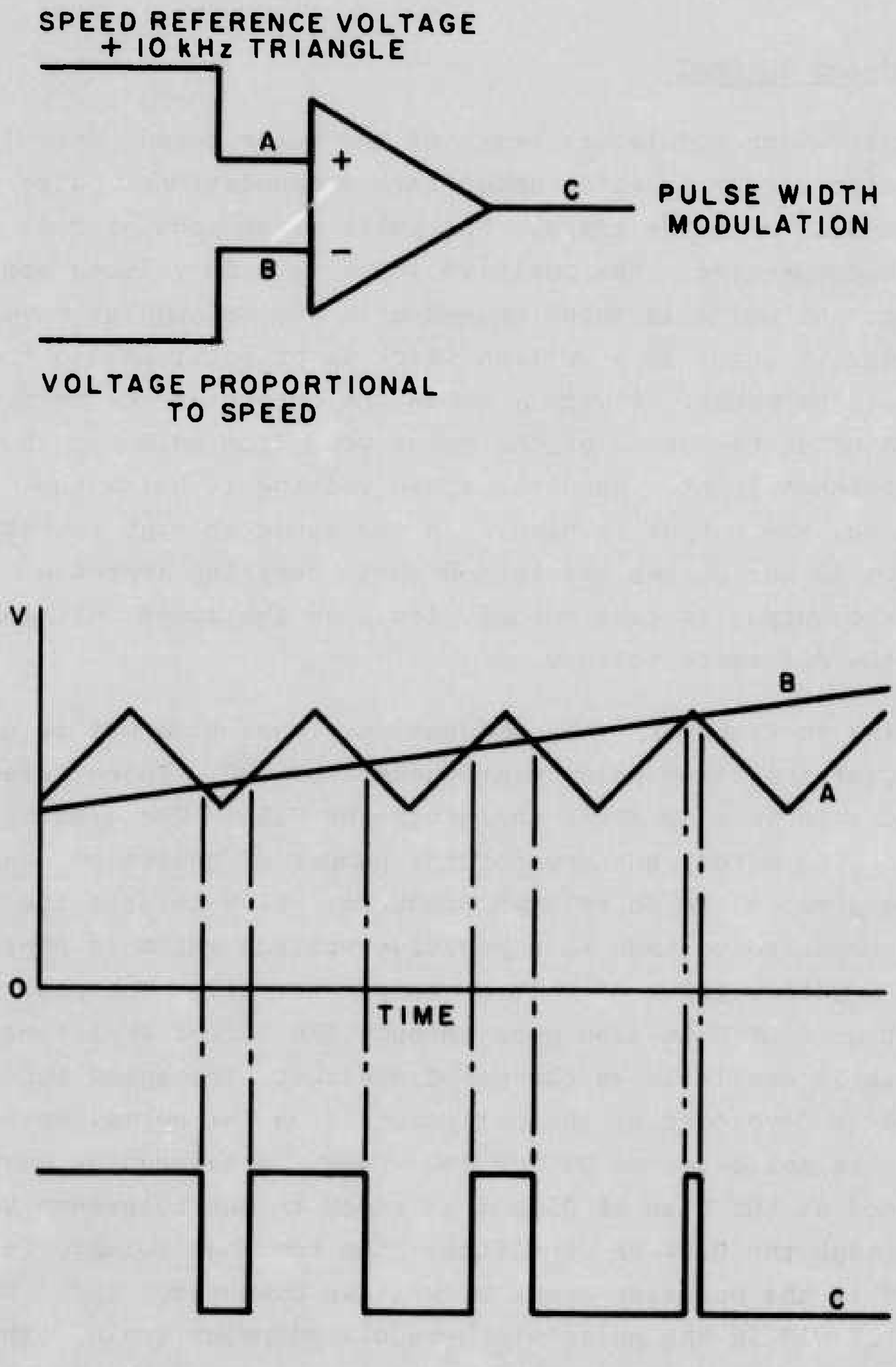

Figure 6: Pulse Width Modulator

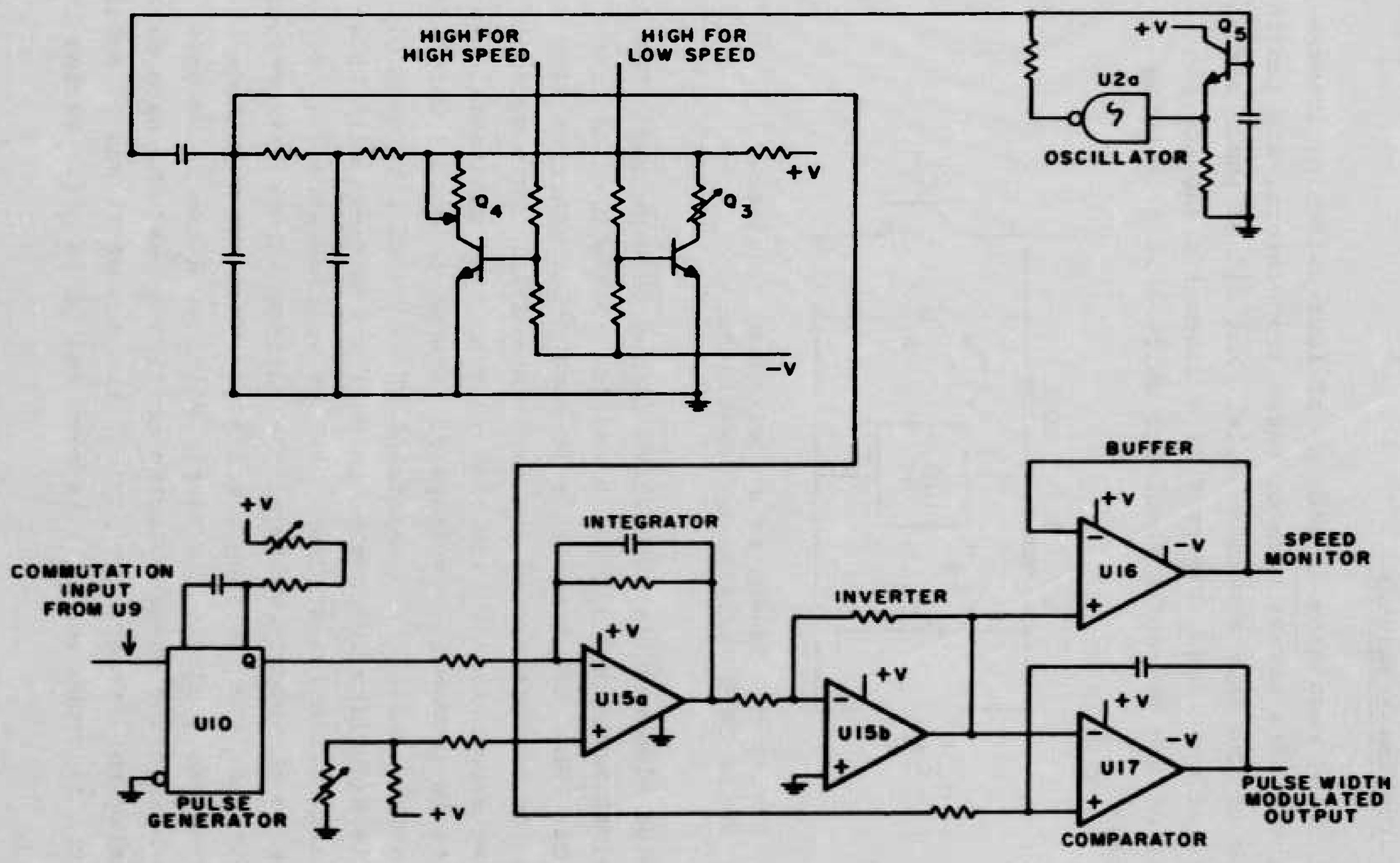

Figure 7: Schematic of Speed Control Circuit

3.4 Switching Regulator

The switching regulator is made up of four switching transistors, the diodes across each of these transistors, and the inductance of the four armature coils. Not all of these elements are used at one time. Figure 8 is a schematic showing the elements of the switching regulator while coil 1 is being commutated.

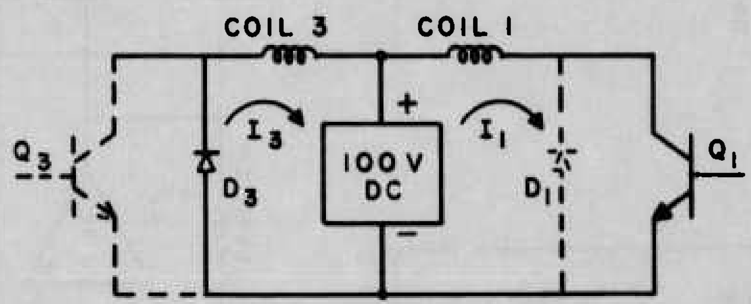

Figure 8: Schematic of Switching Regulator While Coil #1 Is Being Commutated.

The dotted elements are not active during this period. The 10 kHz pulse width modulated signal is applied to the base of transistor Q1. When the transistor is conducting, current flow through the circuit around the path marked I1. This current increases exponentially with time (0.7 ms time constant). As Q1 starts to turn off, a voltage is induced in coil 1 which adds to the supply voltage and maintains the flow of I through Q1. Coil 3 is magnetically coupled to coil 1 and forms with it a unity turns ratio transformer. As the voltage across 1 increases and adds to the supply voltage, the voltage across 3 increases and subtracts from the supply voltage. When the magnitude of the voltage across 2 equals the supply voltage, diode D3 becomes forward biased and current begins to flow around the path marked I3. During this transition period, the sum of I1 and I3 remains constant. I3 grows until I1 is zero and Q1 is off. During the

off period of Q1, I3 decreases linearly with time at a rate which maintains the voltage across coil 3 equal to the supply voltage. When Q1 begins to conduct again, I1 increases at the expense of I3 until I3 is zero and D3 becomes back-biased. I1 again begins to increase exponentially and the cycle repeats. Since coils 1 and 3 are coupled, the magnetic field supplied by current I1 while Q1 is conducting is supplied by current I3 while Q1 is off. The pulse period (100 μs) is small compared to the time constant of the coils (700 μs) so that the variations in the magnetic field due to variations in I1 and I3 are small.

4. PROBLEMS ENCOUNTERED

The system was breadboarded and tested with a dynamometer. The speed regulations were within specification, the efficiencies were better than expected, and the motors were run at twice rated load for several hours and at three times rated load for fifteen minutes without any component failures. Problems were not encountered until the later stages of the program.

4.1 Circuit Redundancy

The first problem occurred when a reliability analysis was made of the breadboarded circuit. Even with the parts count reduced, the mean time between failure was several times less than the desired 100,000 hours. The only way to meet the reliability specification was to add redundant circuits. Two sections of circuit were paralleled, the switching transistor drive chains and the speed regulating circuits. The design problem was to insure that any component failure in one branch would not adversely affect the operation of the corresponding redundant branch. For the switching circuit, the two redundant paths were operated in parallel. In the event of a failure, a diode network would isolate the inputs and fuses would isolate the outputs. For the speed regulating circuit, only one of the two paths was used at one time. In the event of a failure, a failure-detecting circuit switches-in the operating path. To accommodate the added circuits, the number of pc boards had to be increased from 4 to 5, and three piggy-back boards had to be added. It still was possible, however, to make the new boards compatible with the old pc board bin.

4.2 Position-Sensor Signal Processor

When the motors were installed in the crankcase, a capacitive coupling developed between the wires of the coil drive and the wires of the phototransistor sensor. This was due to the tight fit, and resulted in ac leakage into the detector circuit, which interfered with the commutation. The ideal solution would have been to eliminate the capacitance with shielding; however, there was not enough room in the crankcase to permit this. The solution used was filtering in the detector channel and careful adjustment of the ac amplifier gain. Since the leakage capacitance was not a function of temperature as in the case of the dc phototransistor leakage, once the gains of the amplifiers had been set, commutation was stable.

4.3 Current Overload

The original concept of the current overload, which was breadboarded and successfully bench-tested, was, in essence, that of a current limiter. When in the current limiting mode, one of the switching transistors was subject to very heavy power dissipation during starting. With the power applied, but before the motor started, only one transistor was on and limiting the current. Momentary power dissipation in this transistor was 800 W which far exceeded its 120 W rating. As soon as the motor started, the problem disappeared for the back EMF of the motor reduced the amount of power, and the power was spread out among all of the switching transistors. When the drive motor was installed in the cooler, switching transistors began to blow during starts. The motor could not start fast enough with the inertia load of the cooler. The circuit was changed so that instead of limiting the current, the motor was shut down in case of an overload. If the current exceeded 15 A for more than 10 ms, the switching transistors were turned off. To restart the motor, the motor on-off switch had to be first turned off and then turned back on.

4.4 Start Circuit

From Figure 6 it can be seen that when the motor is first turned on, the output of the pulse width modulator is a constant dc level and the full 100 V is applied to the motor. The current rises very rapidly (a 0.7 ms time constant) and if not running within 10 ms, the motor is turned off. With the new overload protection, there were times when the motor could not be started. The circuit was modified so that when the motor switch was off, the speed reference voltage was zero. When the motor switch was turned on, the reference voltage slowly increased over a 15 sec period to its normal value. The acceleration of the motor was then very slow, and the motor current remained low.

5. RELIABILITY ANALYSIS

The parts population method was used to calculate reliability. Failure rates for all components were taken from MIL-HDBK-217A, except those for integrated circuits which were taken from the Texas Instrument Handbook. The circuits were classified by PC boards and by whether or not redundant. PC Board No. 1 contains the speed and logic circuits for the drive motor plus all of the circuits used jointly by the pump and the drive motors. PC Board No. 2 contains speed control and logic circuits for the pump motor. PC Boards No. 3, 4 and 5 contain the switching chains for both the drive motor and the pump motor. The parts count for redundant sections are for only one of the channels.

The reliability data are given in the following tables. From these tables, the failure rate of all circuits is $9.0348/10^6$ hours, which gives a 95.6% chance of 5,000 hours of operation without failure.

Circuit Section	Part Description	MIL-HDBK-217A Reference	Failure Rate $/10^6$ Hrs	Quantity	Total Failures $/10^6$ Hrs	Total Failures $/10^6$ Hrs with Redundancy
PC 1 non redundant	Integrated Circuits	Ref. T.I. Handbook	.18	15	2.7	
	Tant. Elec. Cap.	P 7.6-73	.006	13	.078	
	Ceramic Cap.	P 7.6-53	.0055	39	.21	
	Dipped Mica Cap.	P 7.6-15	.0005	5	.0025	
	Comp. Resistor	P 7.5-11	.0035	72	.25	
	NPN Trans ≤ 1 Watt	P 7.4-13	.222	5	1.11	
	Zener Diode	P 7.4-11	.42	2	.84	
		TOTAL			5.1905	5.1905
PC 1 Redundant	Integrated Circuits	Ref. T.I. Handbook	.18	3	.54	
	Tant. Elec. Cap.	P 7.6-73	.006	3	.018	
	Ceramic Cap.	P 7.6-53	.0055	3	.0165	
	Dipped Mica Cap.	P 7.6-15	.0005	1	.0005	
	Comp. Resistor	P 7.5-11	.0035	15	.0525	
	NPN Trans ≤ 1 Watt	P 7.4-13	.222	3	.666	
	Sil. Diode ≤ 1 Watt	P 7.4-11	.222	3	.666	
	Variable Resistor	P 7.5-31	.57	4	2.28	
		TOTAL			4.28	.0894

Circuit Section	Part Description	MIL-HDBK-217A Reference	Failure Rate /10^6 Hrs	Quantity	Total Failure /10^6 Hrs	Total Failures /10^6 Hrs with Redundancy
PC 2 non redundant	Integrated Circuits	Ref. T.I. Handbook	.18	11	1.98	
	Tant. Elec. Cap.		.006	14	.084	
	Ceramic Cap.	P 7.6-53	.0055	34	.197	
	Comp. Resistor	P 7.5-11	.0035	51	.179	
	Zener Diode	P 7.4-11	.42	2	.84	
		TOTAL			3.28	
PC 2 Redundant	Integrated Circuits	Ref. T.I. Handbook	.18	3	.54	
	Tant. Elec. Cap.	P 7.6-73	.006	2	.012	
	Ceramic Cap.	P 7.6-53	.0055	3	.0165	
	Dipped Mica Cap.	P 7.6-19	.0005	1	.0005	
	Comp Resistor	P 7.5-11	.0035	11	.0385	
	Variable Resistors	P 7.5-31	.57	3	1.71	
		TOTAL			2.3175	0.0269

Circuit Section	Part Description	MIL-HDBK-217A Reference	Failure Rate /10^6 Hrs	Quantity	Total Failures /10^6 Hrs	Total Failures /10^6 Hrs with Redundancy
PC 3, 4, 5 Redundant	Comp. Resistor	P 7.5-11	.0035	4	0.0140	
	NPN Trans > 1 Watt	P 7.4-13	.444	1	0.44	
	PNP Trans > 1 Watt	P 7.4-13	1.12	2	2.24	
	Diode > 1 Watt	P 7.4-11	.34	1	0.34	
	Diode < 1 Watt	P 7.4-11	.222	1	0.222	
	Fuse	P 7.12-3	0.1	1	0.1	
		TOTAL			3.355	0.056

		Total Failures /10^6 Hrs with Redundancy
PC 1	non redundant	5.1905
PC 1	redundant	0.0894
PC 2	non redundant	3.28
PC 2	redundant	0.0269
PC 3, 4, 5	8 channels (8 x 0.056)	0.448
	TOTAL ALL CIRCUITS	9.0348

6. TEST RESULTS

The motors and the control electronics were bench-tested with a dynamometer load. Figure 9 shows the overall drive motor system efficiency versus torque; Figure 10 shows the pump motor system efficiency versus torque. It was originally planned that the normal speed of the drive motor would be 420 rpm and the standby speed would be 250 rpm. This was changed to 350 rpm and 220 rpm, respectively. The operating torque of the drive motor is about 1000 in-oz. The design goal of 55% efficiency at normal speed was achieved. The goal of 50% at standby speed was missed by about 5%. The operating point of the pump motor was 1750 rpm and 30 in-oz of torque. The efficiency at this point was also about 5% below the design goal of 55%.

Table 1 shows the power losses for the two systems under various operating conditions. The power output and power losses are normalized to a percentage of the power input. The major sources of loss in the two systems are regulator losses and armature I^2R losses. As the torque increases, the armature losses increase while the regulator losses decrease. This causes the efficiency to be relatively insensitive to changes in torque. Both armature and regulator losses decrease with speed. This means that the efficiency is strongly dependent on speed. It is important, therefore, in the design of a system, that the operating speed be accurately estimated so that the system efficiency can be optimized at that speed. The speed regulation was less than $\pm$ 1% for voltage changes between 103 and 97 volts. A regulation of $\pm$ 3% was obtained for load variations from zero to twice the rated load. A circuit change made after the motors were installed in the cooler approximately doubled these values. The motor system should still be well within the design goal of $\pm$ 3% over the 103 V to 97 V range.

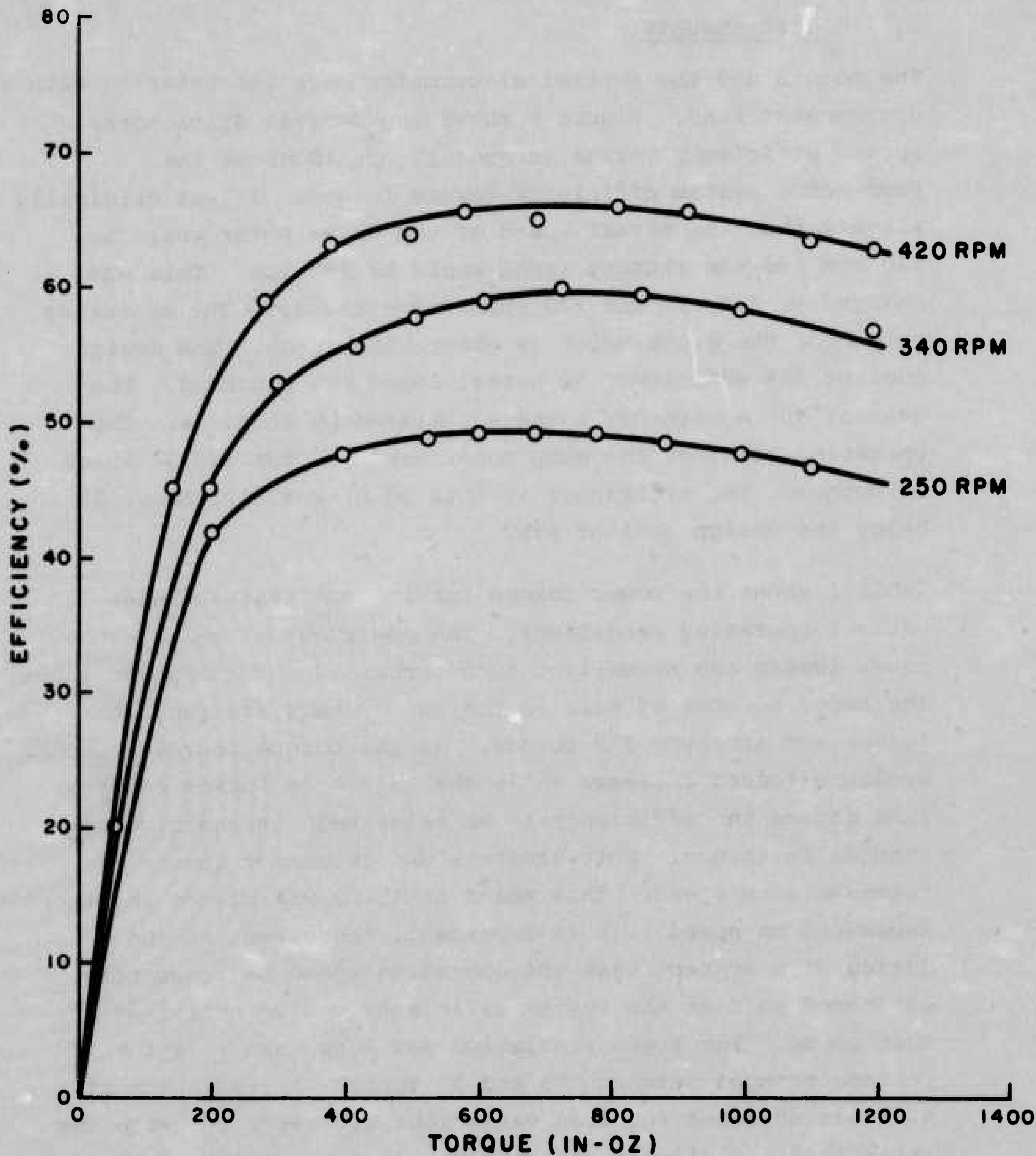

Figure 9: Drive Motor Efficiency vs. Torque

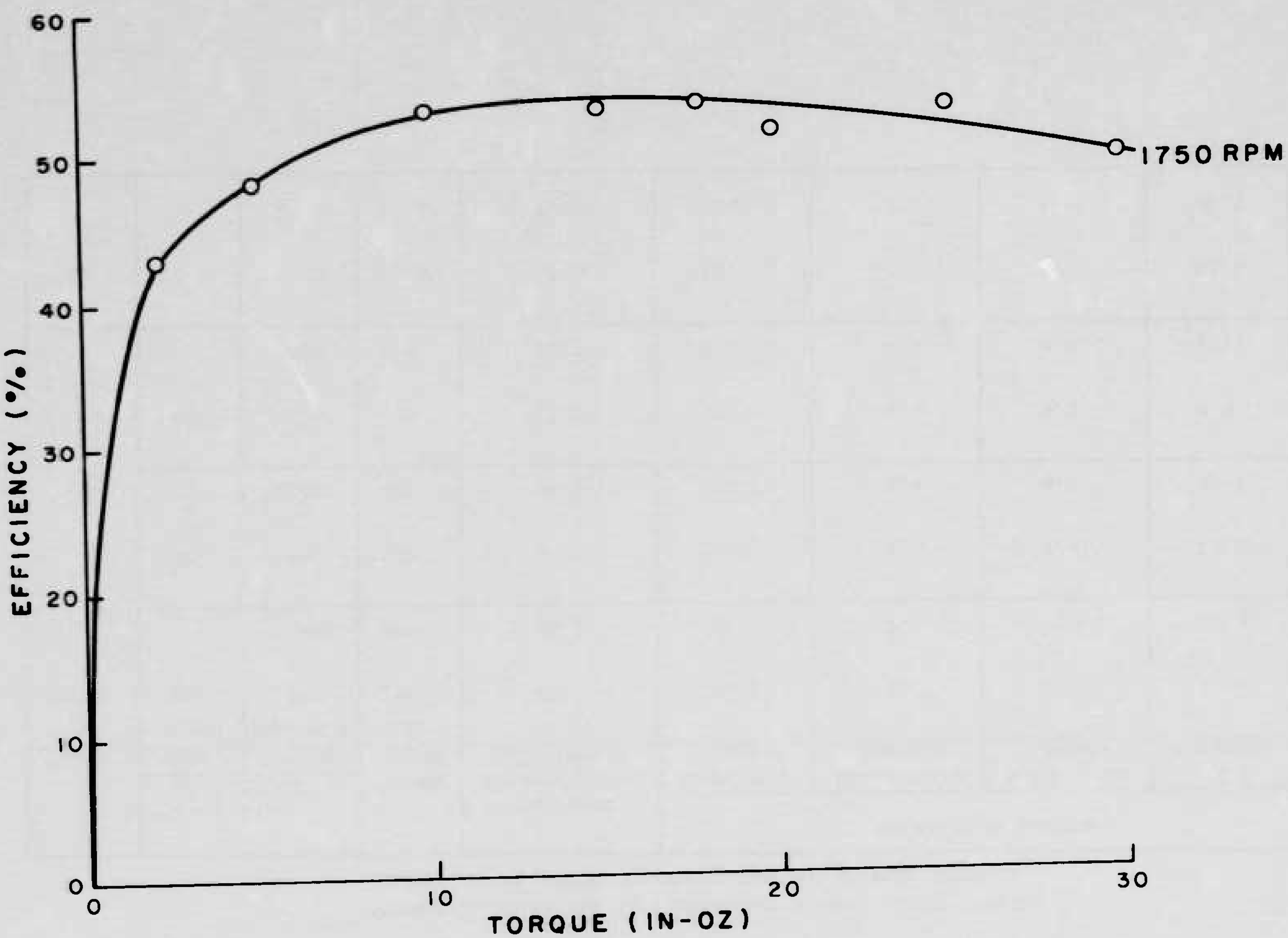

Figure 10: Pump Motor Efficiency vs. Torque

TABLE I

Power Losses of Drive Motors and Pump Motor Normalized to a Percentage of Power Input.

Motor	Operating Conditions		Power Input	Normalized Power Output (Efficiency)	Normalized Losses				
	Speed	Torque			Regulator Losses	Electronic Control	Rotational Losses	I^2R Armature	Other
	(rpm)	(in.oz.)	(W)						
Drive	250	500	190	48.7	26.8	5.3	5.8	12.1	1.3
		1000	384	48.2	20.6	2.6	2.9	21.4	4.4
	340	500	220	57.7	18.0	4.5	7.7	10.5	1.4
		1000	425	58.8	13.6	2.4	4.0	19.1	2.1
	420	500	235	63.8	11.1	4.3	9.8	9.8	1.3
		1000	475	64.7	6.5	2.1	4.8	17.3	4.8
Pump	1750	17.5	42.4	53.5	15.3	4.7	3.3	21.5	1.7
		30.0	79.4	49.0	7.9	2.5	1.8	32.6	6.2

☆ U. S. GOVERNMENT PRINTING OFFICE: 1975 — 657-630/248